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CORPORATE RESEARCH AND DEVELOPMENT
Schenectady, N.Y.

EXECUTIVE SUMMARY OF FINAL REPORT ON PHASES 1 AND 2
VHF RANGING AND POSITION FIXING EXPERIMENT USING ATS SATELLITES

25 November 1968 - 1 May 1971

Contract No.: NAS5-11634

Prepared by
GENERAL ELECTRIC COMPANY
Corporate Research and Development
Schenectady, New York

for

Goddard Space Flight Center
Greenbelt, Maryland

This separately bound summary presents highlights selected from the experiment descriptions and data presented in the complete report with this same title and number. Results of all the experiments are consistent with those presented in this summary.

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Contract No.: NAS5-11634

Goddard Space Flight Center

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ACKNOWLEDGEMENT

The National Aeronautics and Space Administration provided support and cooperation that made the experimental program possible. Especially valuable was the program guidance and coordination of the Technical Monitor, Mr. Charles N. Smith, and his colleagues at Goddard Space Flight Center. NASA's ATS Operations and Control made generous allowances of time on the ATS-1 and ATS-3 satellites. They often worked hard to schedule satellite time so that we could take advantage of opportunities that became available within limited time periods.

Many other organizations in the United States and abroad participated voluntarily in the experiments. Every request for cooperation met an enthusiastic and professionally executed response. The following is a listing of the major participants, in addition to NASA and General Electric.

Federal Aviation Administration - Flight testing, often with flights devoted exclusively to the experiments, with DC-6 and C-135 aircraft; radar tracking of aircraft, data collection and analysis.

US Coast Guard - Installation and operation of transponders aboard Coast Guard cutters in port and underway in the Gulf of Mexico and the Pacific Ocean.

Office of Naval Research - Support, under contract N00014-68-C-0467, and cooperation in experiments with the Sea Robin buoy at Bermuda.

Aeronautical Radio, Inc. - Arrangements with foreign governments and airlines for equipment installations and experiments. Communications tests with ARINC Laboratories.

Argentine Air Force - Installation, operation and maintenance of a transponder at Buenos Aires.

Boeing Company - Installation, operation, and maintenance of a transponder at Seattle, Washington.

Canadian Department of Transport - Installation, operation, and maintenance of a transponder at Gander, Newfoundland.

Iceland Civil Aviation Administration - Installation, operation, and maintenance of a transponder at Reykjavik, Iceland.

Irish Department of Posts and Telegraphs - Installation, operation, and maintenance of a transponder at Shannon, Ireland.

COMSAT Corporation - Independent measurements of ranges from satellites to transponders. Computation of range measurement precision for comparison with GE data.

Pan American Airways - Integration and test of tone-code responder with Satcom equipment on 747 aircraft. Communication tests through ATS-3 from 747 aircraft on commercial flights.

Air Force Cambridge Research Laboratories - Cooperative ionospheric propagation measurements, data on ionospheric characteristics.

The General Electric experiment team values the many friendships that were developed with members of each of the participating organizations. It was our privilege to have personal association with many of them. With others, our contacts were by long distance communications, including voice transmissions

through the satellites. Each participant made a valuable contribution to the experiment through the exercise of professional skill and cooperation that was enthusiastic even when it was at personal inconvenience. It is our sincere hope that each participant benefitted from the work, and that the excellent relationships that were developed will continue.

EXECUTIVE SUMMARY

Abstract

The VHF transponders of the ATS-1 and ATS-3 geostationary satellites were used in ranging and position fixing experiments. An interrogation signal was transmitted from a ground terminal to ATS-3, which relayed it to the vehicle transponders. The vehicle that was addressed repeated the signal and its response was relayed back through both satellites to the ground terminal, where propagation times were measured; lines-of-position and fixes were computed. The 0.43 second "tone-code" ranging signal contained a single audio tone frequency. Ambiguity was resolved and user craft identified by a simple digital code.

Seven vehicles were used in the test: three aircraft, two ships, an oceanographic buoy, and a truck. Ionospheric and multipath effects were studied.

It is concluded that a VHF system could have an accuracy of ± one nautical mile for ships and aircraft if calibration transponders are used to monitor the ionosphere.

Introduction

A two and one-half year testing program with the National Aeronautics and Space Administration's ATS-1 and ATS-3 spacecraft has shown that geostationary satellites can provide superior communications and position surveillance for mobile craft. The tests proved that inexpensive modifications to conventional mobile communications equipment aboard the craft can provide reliable, high quality voice and digital communications with distant ground stations and other vehicles and automatic surveillance of the positions of all the craft by a ground facility. The tests also demonstrated the location and automatic read-out of remote data collection platforms.

Frequency modulation signals with the narrow audio and radio frequency bandwidths of terrestrial mobile radio communications were relayed through the VHF transponders of the geostationary satellites. The voice and digital communications were far superior in reliability and quality to long-distance mobile communications by other means such as medium or high frequency radio. One satellite provides nearly uniform high quality performance over approximately one-third of the earth's surface.

Position fixes by range measurement from the two satellites were accurate to approximately one nautical mile, one sigma except near the equator and the poles. The ranging signals were narrow bandwidth FM like the voice and digital signals, and were highly compatible with the communications. A single interrogation yielded range measurements from two satellites so that a position fix could be determined in about one second of time. The technique can be modified to locate several craft within a second.

Satellite communications with mobile craft and data collection platforms and independent surveillance of their positions is practical at VHF (118-174 MHz). There is no question that a system could be implemented with technology that is immediately available and that user equipment would be inexpensive, reliable and convenient.

Transmission link reliability was not adequate for operational use under all conditions of the test. Factors affecting its reliability were identified and measured. Link performance could be improved to operational acceptability with modest engineering changes to the satellite and user equipment designs such as the use of circular polarization of the satellite and more suitable antennas on the mobile craft.

The performance of VHF satellite transmission links is degraded in performance due to ionospheric propagation effects at some times and places, especially in tropical and high latitude regions. The system can be designed to minimize the propagation effects and provide operationally acceptable performance under almost all conditions.

The use of VHF for satellite applications is restricted because there is not an adequate number of radio frequency channels to fulfill the anticipated requirements. Data collected during the experiment can be used to estimate the performance that would be achieved with other system parameters and ranging techniques at higher frequencies, such as L-band, where channels can be assigned more easily and where ionospheric propagation disturbances are less than at VHF.

Experiment Procedure

General Electric's Radio-Optical Observatory near Schenectady, New York was the base for the experimental program. Ranging interrogations originated there, ranging time intervals were measured, data recorded, and a computer terminal was used in processing data and computing fixes.

Seven vehicles were used in the tests: a Coast Guard Cutter in the Gulf of Mexico and one in the Pacific Ocean; three aircraft, a DC-6B and a C-135 of the Federal Aviation Administration, and a 747 aircraft of Pan American Airways; a buoy moored in deep water off Bermuda; and a panel truck in up-state New York. In addition, there were fixed ground reference transponders at Shannon, Ireland; Reykjavik, Iceland; Gander, Newfoundland; Seattle, Washington; and Buenos Aires, Argentina. Each vehicle and ground station was equipped with a conventional mobile communications transmitter and receiver and a suitable antenna, and had a 6 x 8 x 10 inch, 6 pound experimental tone-code responder unit attached between the receiver and transmitter. The combined receiver, transmitter and responder is termed a transponder.

Each of the ground reference transponders consisted of a mobile radio base station unit, like those used by a taxi cab dispatcher, with a physically small 300 Watt power amplifier and an eight-turn helical antenna. A tone-code responder was connected between the transmitter and receiver of the base station unit. The units are inexpensive, easily installed by a local technician, and are fully automatic. They can be turned on by interrogation through the satellite and respond automatically with no person present.

Ground stations as well as the mobile units in the ships and aircraft were useful for voice communications as well as ranging for position fixing. The unit in the buoy responded with an automatic digital read-out of its onboard sensors each time it was interrogated for a ranging measurement.

When a vehicle was to be located, a ground station transmitted a 0.43 second tone-code signal to one of the satellites, the "interrogating satellite", usually ATS-3. The signal consisted of a 2.4414 kHz tone burst followed by the individual user address formed by suppressing an audio cycle for a digital "zero" and transmitting an audio cycle for a digital "one". The tone-code signal was frequency modulated on a 149.22 MHz carrier with a narrow deviation so that the RF bandwidth was within the 15 kHz bandwidth of the mobile receivers.

The satellite repeated the signal on 135.6 MHz. All of the activated vehicle equipments received the signal, and each matched the phase of a locally generated audio tone to the received tone phase. The one vehicle that was addressed responded with a short burst of its properly phased locally generated tone followed by its address code, introducing a very precisely known time delay between reception and retransmission of the code. The vehicle response on 149.22 MHz was through a broad beamwidth antenna. If both satellites were in range of the vehicle, they both repeated it on 135.6 MHz.

The ground station received the returns from the two satellites separately with narrow beamwidth antennas. It measured the time interval from its initial transmission of the signal to the first return from the interrogating satellite and to the two returns from the satellites as they were relayed back from the user. (Figure 1) From these measurements, the ranges from the two known positions of the satellites to the vehicle were determined. These ranges, together with vehicle altitude and corrections for ionospheric delay, were used to compute the vehicle location. When only one satellite was in range of the vehicle, a line of position was computed and a fix defined as the crossing of the line with latitude or longitude of the vehicle determined by other means.

The time required for the interrogation and response was approximately one second except when a data transmission followed the user's tone-code ranging response. The usual interrogation rate was once every three seconds. A modification to the tone-code signal design is expected to reduce the duration of the signal to 30 milliseconds. In an operational system it would be possible to order the interrogations so that several position fixes could be made within one second.

The tone-code ranging technique has the following characteristics:

- Useful accuracy can be achieved within the modulation and radio frequency bandwidths of present-day mobile communications.

- The technique can be used with wide bandwidth for high accuracy.

- It requires only one channel for range measurements, receiving and transmitting in the simplex mode if desired without need for an antenna diplexer.

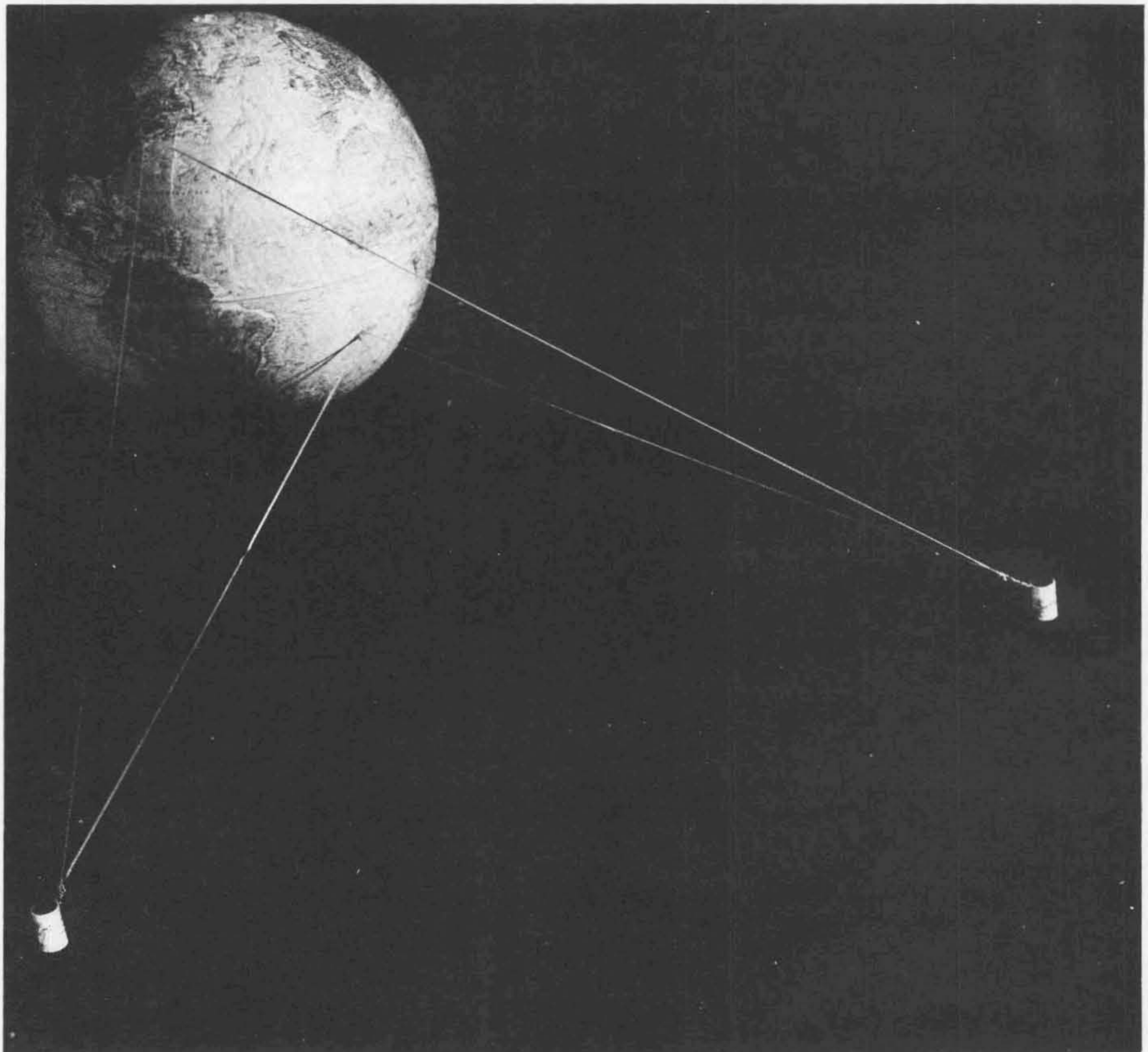
- The time required for the range measurements is a fraction of a second so that the ranging function can time-share a communication channel with little additional time usage of the channel.

- It can be implemented by the addition of an inexpensive, solid state responder unit attached to a communication receiver-transmitter.

- It can, but need not, employ digital or digitized voice transmissions to provide synchronizing of the user responder, thereby further increasing the efficiency of channel usage.

FIGURE 1

SYSTEM CONCEPT



- There are no "lane" ambiguities in the range measurements.

- User identification is simple and is confirmed in the return signal.

Ship Tests

A tone-code transponder, like the one shown in Figure 2, was installed on the Coast Guard Cutter Rush at San Francisco on May 5, 1970. The transmitting antenna used on the Rush is shown in Figure 3. The equipment time delay was calibrated after installation by ranging through the satellites while the ship was underway in the Gulf of Farallons near San Francisco on May 5. A refined measurement of the time for the signal to pass through equipment after it is installed is necessary, since the equipment time delay must be subtracted from the total ranging time measurement in order to yield the propagation time of the radio signal from the satellite to the vehicle and return.

On May 10 the ship was at the dock, shown in the center of the right-hand one mile radius circle in Figure 4. The ship was interrogated through ATS-3 and its responses were received back through ATS-1 and ATS-3 to yield range measurements from the two satellites so that the position fixes could be computed. Three fixes determined on that date are shown just outside the one nautical mile radius circle on the upper left. The ship then proceeded to its weather station duty half-way between San Francisco and Hawaii where it remained for three weeks. Many position fixes were determined while the ship was enroute and at the weather station. It then continued on to Pearl Harbor, Hawaii, where it was in view of only one satellite, ATS-1. Range measurements from ATS-1 were used to determine the latitude of the ship while it was docked at Pearl Harbor. The latitude determinations bracketed the actual position of the ship within one nautical mile. The ship returned to San Francisco and was again tied up at the dock in the center of the right-hand circle. The position fixes shown near the lower edge of the circle were made by satellite ranging on July 10. All of the fixes can be enclosed in a 5,000 foot radius circle. The ship was at the dock in the center of the left hand circle on July 21 and the small ovals are the position fixes determined on that day. Each set of position fixes is biased from the true position. A study of the satellite position predictions as stated by NASA show that the predicted positions for the satellites which are the references for the fix determinations can be in error by amounts that could cause position fix bias errors larger than those plotted in Figure 4.

No adjustment was made to the equipment while it was installed on the Rush. The only human attention given to it was to turn on the main power in anticipation of the satellite experimental periods and to use the equipment for voice communications through the satellite with the network of ground transponders and with other ships in the Atlantic Ocean. The quality of the voice communications was excellent.

Aircraft Tests

Two transponders were used aboard aircraft of the Federal Aviation Administration. One of the units was a transponder like the one used on the ships. The other consisted of an RTA-41B transceiver with a frequency modulation modem and a 500 Watt power amplifier. A General Electric tone-code responder was connected between the transmitter and receiver of the RTA-41B unit.

FIGURE 2

GROUND REFERENCE TRANSPONDER

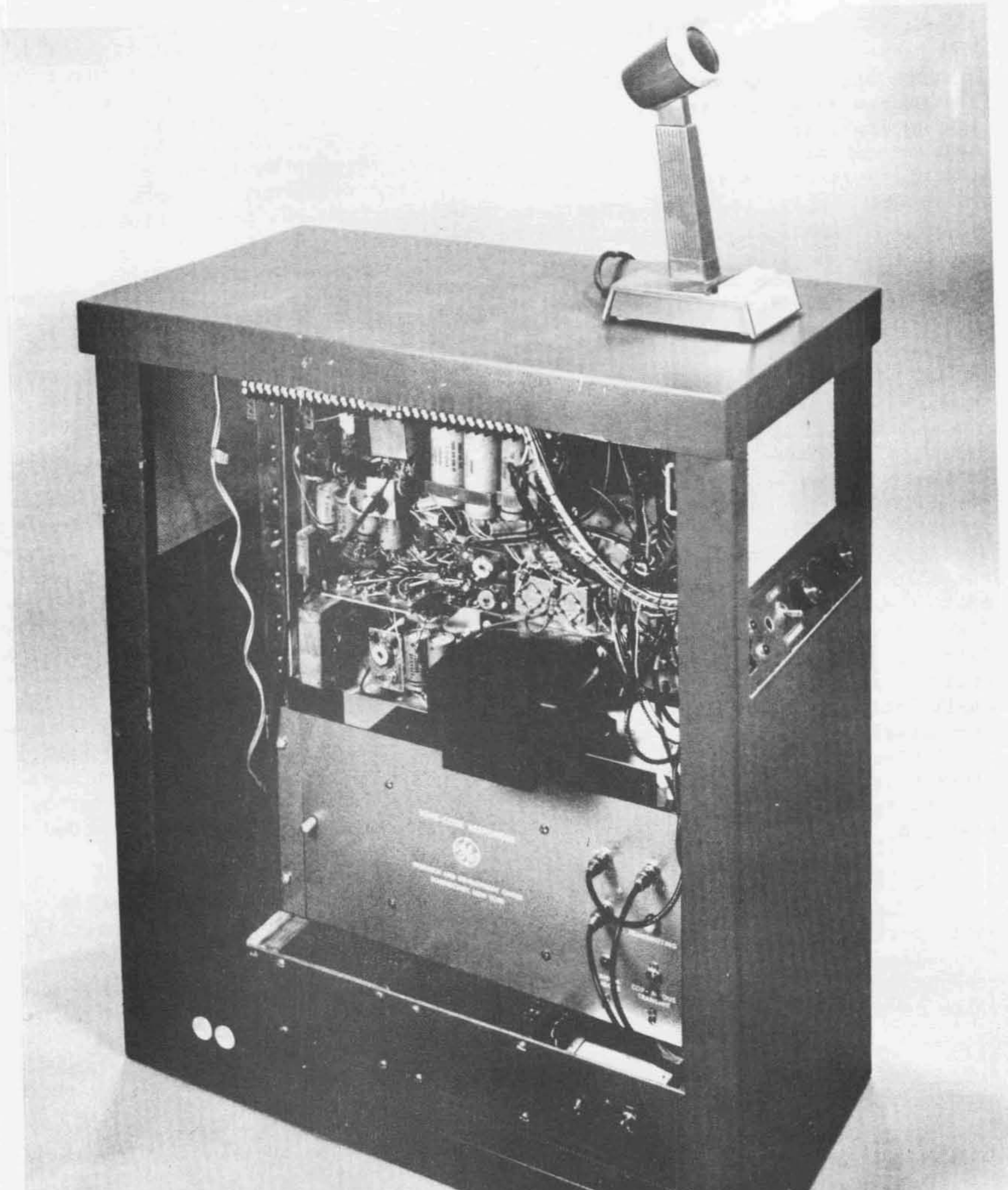


FIGURE 3

CIRCULARLY POLARIZED TURNSTILE ANTENNA

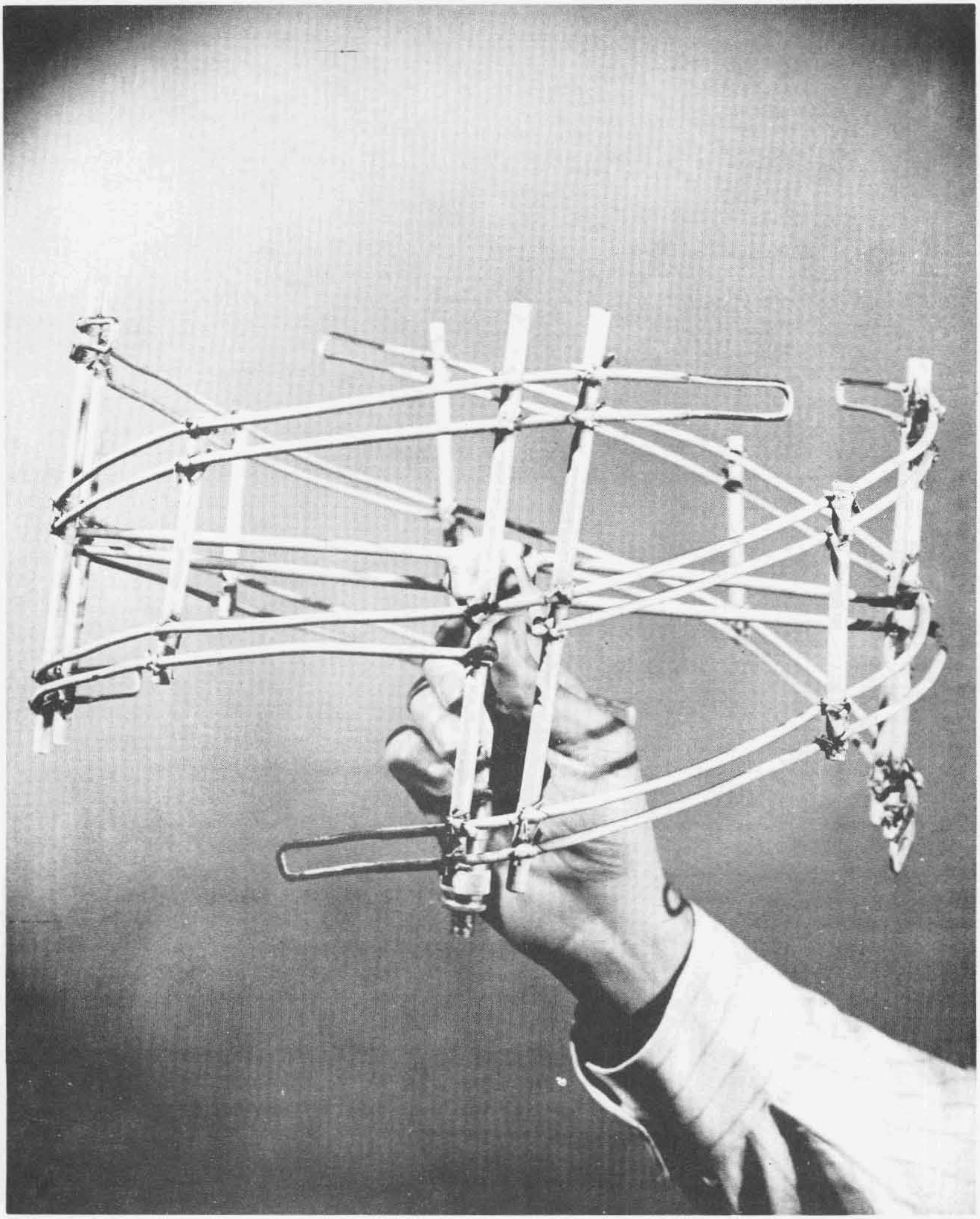
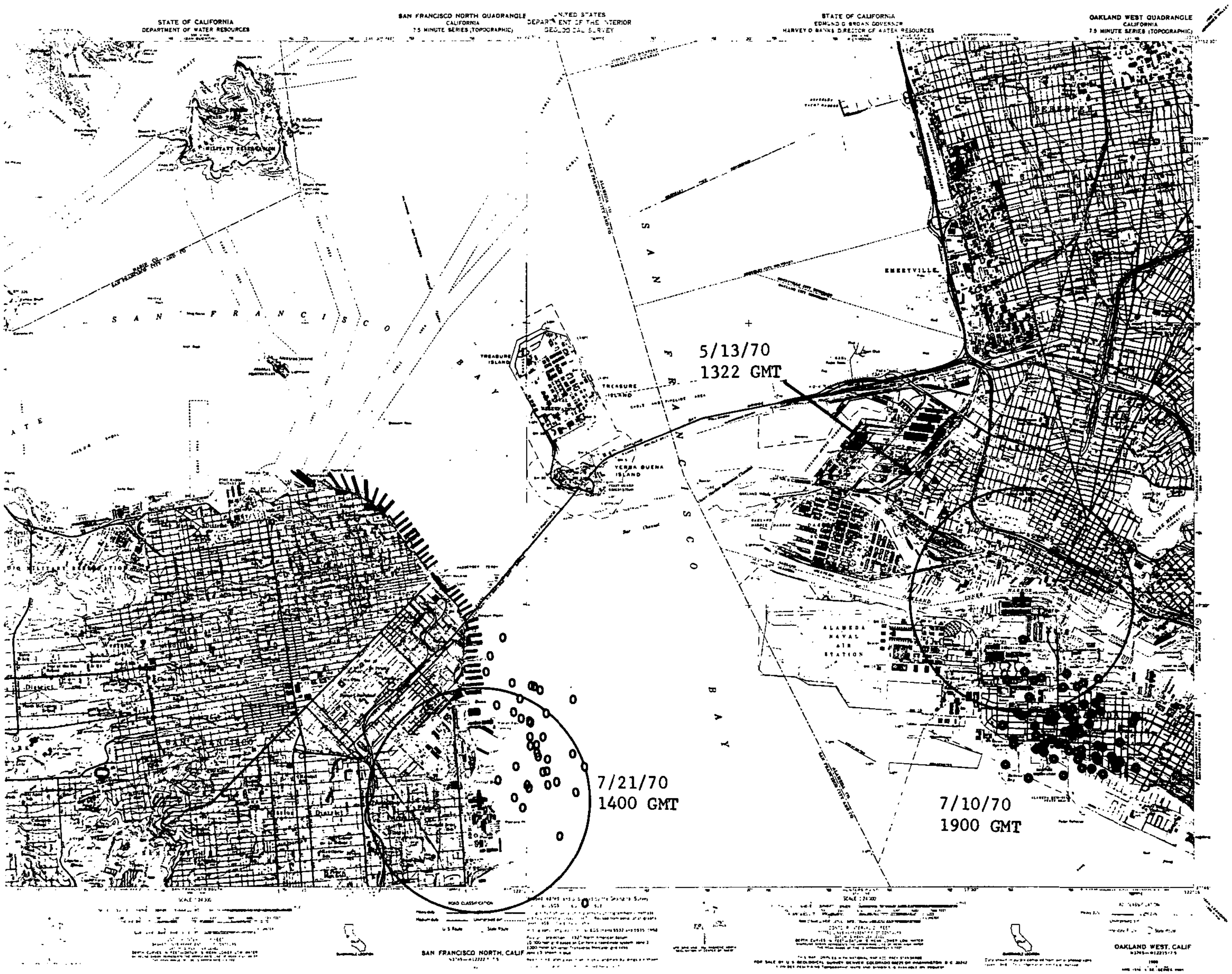


FIGURE 4

POSITION FIXES, COAST GUARD CUTTER RUSH IN SAN FRANCISCO BAY



Antennas used aboard the aircraft included a conventional VHF blade modified to transmit 500 Watts at the up link frequency of 149.22 MHz and a Dorne and Margolin Satcom antenna. The Satcom antenna is circularly polarized in two modes. The horizon mode is omnidirectional in azimuth and it has a vertical coverage from 10 degrees to 40 degrees elevation. The zenith mode is also circularly polarized and covers a solid angle from approximately 40 degrees elevation upward. Both modes have a maximum gain of approximately 3 dB.

Figure 5 compares the two-satellite position fixes shown as crosses with precision radar fixes shown as dots as the DC-6 aircraft left the National Aviation Facilities Experimental Center of the FAA at Atlantic City. The solid lines are one nautical mile on each side of the precision radar track.

When the aircraft arrived at Shannon, Ireland, it was parked on a bench mark. It was in view of only the ATS-3 satellite, being too far east for ATS-1. Range measurements from ATS-3 were used to compute the latitude at which the satellite line of position crossed the known longitude of the bench mark. The average of 14 range measurements was 800 feet north of the bench mark. The largest single errors were 7500 feet north and 6000 feet south of the bench mark. Three range measurements to the ground reference transponders at Shannon were used to derive a correction for the sum of range errors due to ionospheric propagation delay and satellite position prediction uncertainty, thus testing the concept of using ground reference transponders for real time corrections of the range measurements. Long term stability of the equipment time delay was verified in this test because the equipment time delay calibration for the aircraft was made nine days different in time when the aircraft was at Atlantic City.

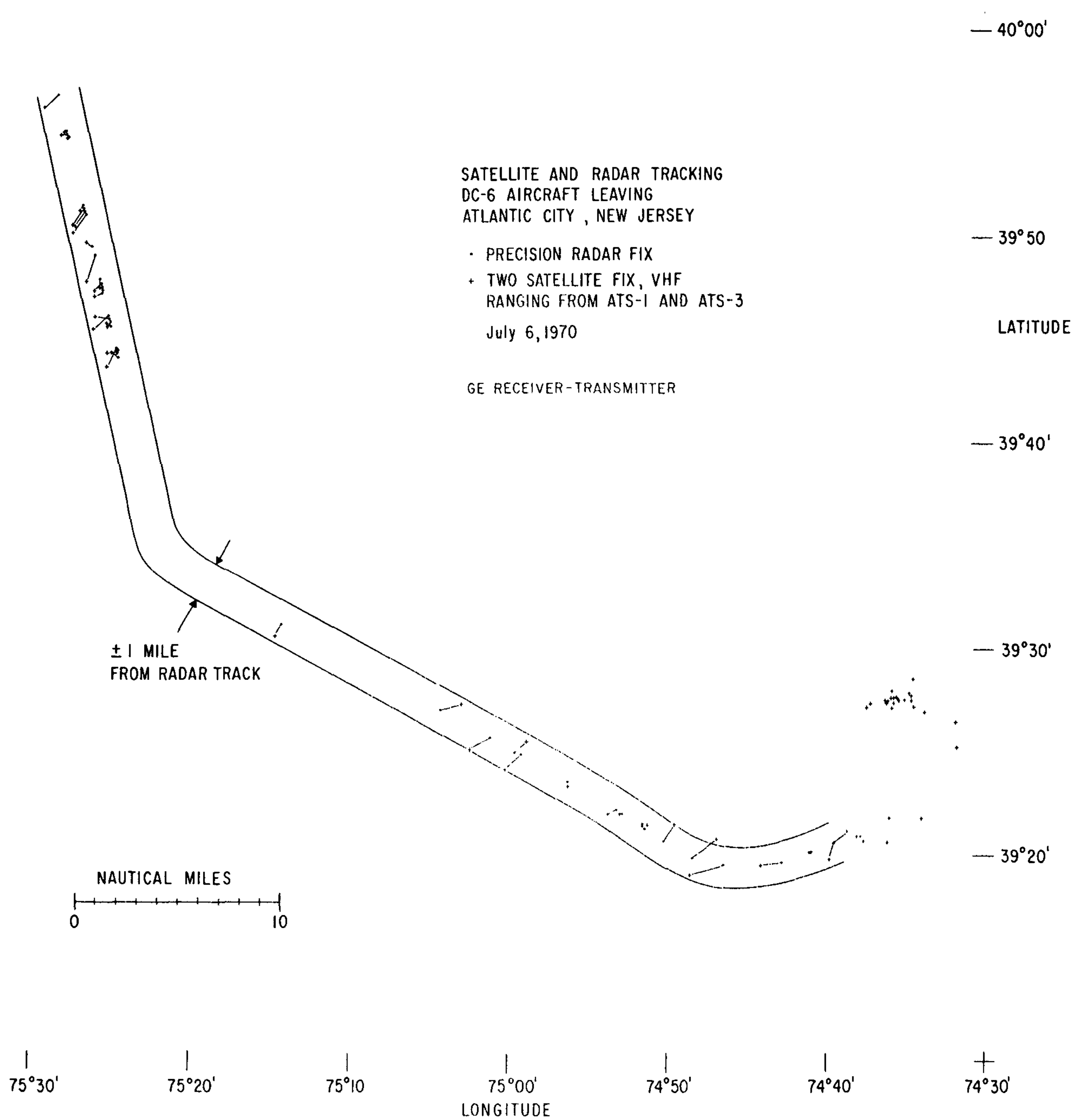
The Federal Aviation Administration provided many hours of flight time for the satellite ranging and communication experiments with a DC-6 four engine propeller driven aircraft and a C-135 jet aircraft.

One 5.5 hour flight test with both aircraft was made within range of the precision EAIR radar at Atlantic City. Tests were made over water east of the New Jersey Coast and over land northwest of Philadelphia. The aircraft were flown at two altitudes, approximately 20,000 feet and 5,000 feet, and at various headings.

Each satellite fix was plotted relative to the radar fix of the aircraft made at the same second of time. Figure 6 is a plot of the satellite fixes relative to the radar fixes for the DC-6, the radar fix references being the center of the circle. The divisions are one minute in latitude and longitude. The radius of the circle is 10 nmi., representing the Boeing accuracy specification after five hours of flight for the Inertial Navigation Systems used aboard the 747 aircraft. The specification states that the Inertial Navigation System shall accumulate no more than 2 nmi. error per flight hour on 95 percent of flights up to ten hours duration. (Edwin L. Hughes, "Inertial Navigation for 747 Superjet", Electronics World, 9/70, p. 27).

One satellite fix with the DC-6 aircraft was in error by 11 miles. It is the worst single fix noted in the entire ranging and position fixing experiment, except for a small number of fixes that were displaced by multiples of 75 miles along a hyperbolic line of position in the aircraft experiments. The large fix errors were caused when the aircraft responder-correlator output occurred a multiple of a bit period early. The bit or tone-code cycle period is 409 microseconds. Errors of that type were rare in the experiment and their occurrence can be reduced to an insignificant probability by improvements in the correlator

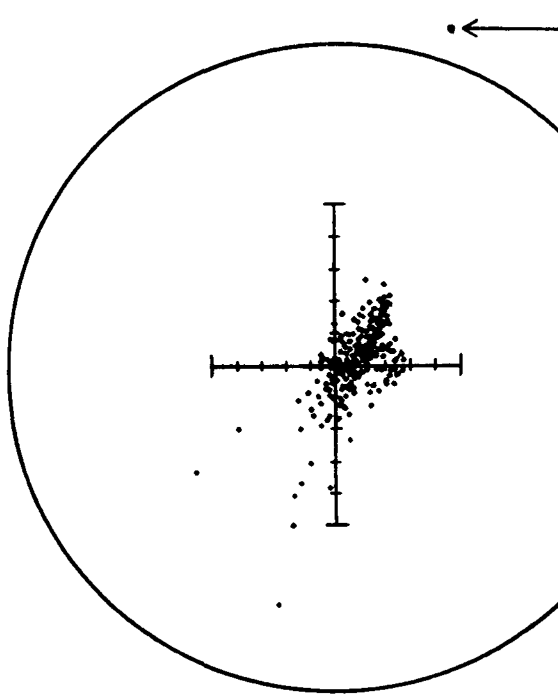
FIGURE 5



SATELLITE AND RADAR TRACKING
DC-6 AIRCRAFT LEAVING
ATLANTIC CITY , NEW JERSEY
· PRECISION RADAR FIX
+ TWO SATELLITE FIX, VHF
RANGING FROM ATS-I AND ATS-3
July 6, 1970
GE RECEIVER-TRANSMITTER
40°00'
39°50
39°40'
39°30'
39°20'
LATITUDE
± I MILE
FROM RADAR TRACK
NAUTICAL MILES
0
10
75°30'
75°20'
75°10
75°00'
74°50'
74°40'
74°30'
LONGITUDE

FIGURE 6

ACCURACY OF AIRCRAFT FIXES
5.5 HOUR FLIGHT
DC-6
"WORST CASE" CONDITIONS



10 nmi. RADIUS CIRCLE

and code designs. The pattern of position fix errors for the C-135 were similar to the DC-6. There was a larger scatter caused by receiver time delay change with signal amplitude, but no C-135 fixes were outside of the 10 nmi. radius circle, except for a few that were multiples of 75 miles in error.

A study of the aircraft fix errors as a function of time during the 5.5 hour flight reveals the changing bias error due to the diurnally changing satellite prediction errors. The plot of Figure 7 includes the bias errors due to satellite position fixes. There were no corrections for any of the known causes of error in the plots. Figure 7 represents a comparison of the worst conditions for the two satellite ranging at VHF with the specified performance for an aircraft inertial navigation system after 5 hours of flight time.

Nominal accuracy, as exemplified by the ship tests, equaled the accuracy specified for the Inertial Navigation System after one hour of flight time. Precision of the satellite fixes is poorer than the Inertial Navigation System, but long term accuracy is better because the satellite surveillance does not accumulate significant error during a flight or a ship voyage. If Inertial Navigation System accuracy is adequate for maintaining separations of aircraft on transoceanic flights, it is evident that the more accurate tone-code ranging technique with satellites is also adequate.

Propagation Measurements

The widespread network of ground reference transponders was used in tests to measure the propagation and other factors that affect the accuracy of a satellite position fixing system operating at VHF. The experimentally derived information about propagation and other error contributing factors can be used to predict the performance of satellite ranging systems at higher radio frequencies and with different system parameters.

The propagation velocity of radio waves is reduced as they pass through the ionosphere. The reduction in velocity is proportional to the integrated electron content along the ray path and to $1/\text{frequency}^2$. The reduced propagation velocity increases propagation time and therefore causes an apparent increase in range measurements. There are two ways to correct for the propagation delay. One way is to estimate the delay by the use of a model of the ionosphere based on the large quantity of data that has been collected over the past several decades. The other way is to measure the propagation delay at a known location and use the measurement to correct range measurements made to other transponders in the geographical region surrounding the known location.

Both ways of correcting for propagation delay were used in the experiments. A simple model provided corrections adequate for position fix accuracy better than 1 nmi., 1 sigma. The other method, using reference transponders at known locations, was also effective and provided the additional benefit of a first order correction for error in satellite position prediction.

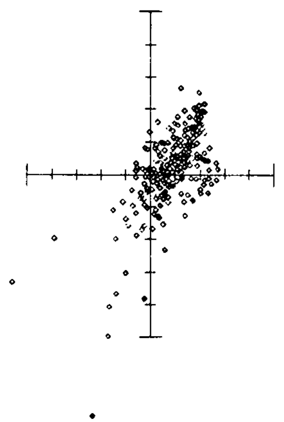
A model is useful if there are predictable cyclic changes in the ionosphere. The diurnal cycle is the dominant one. The day-to-day correlation of ionospheric delay is thus important in estimating the value of a model.

The usefulness of reference transponder measurements depends upon the correlation of ionospheric delay at one location with the delay at another. The geographical extent of the correlation is important in evaluating the practical

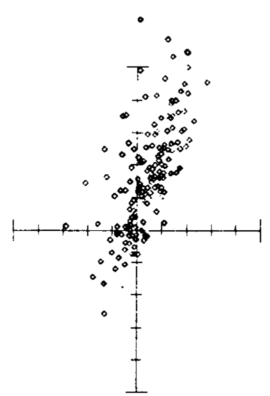
FIGURE 7

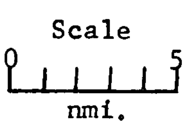
POSITION FIX ACCURACY COMPARISONS

DC-6 FIX ERRORS - 5.5 HOUR FLIGHT - 12/1/70
"WORST CASE" CONDITIONS"--(One other fix in error by 11 miles - see Figure 29 in the Aircraft Tests Section)



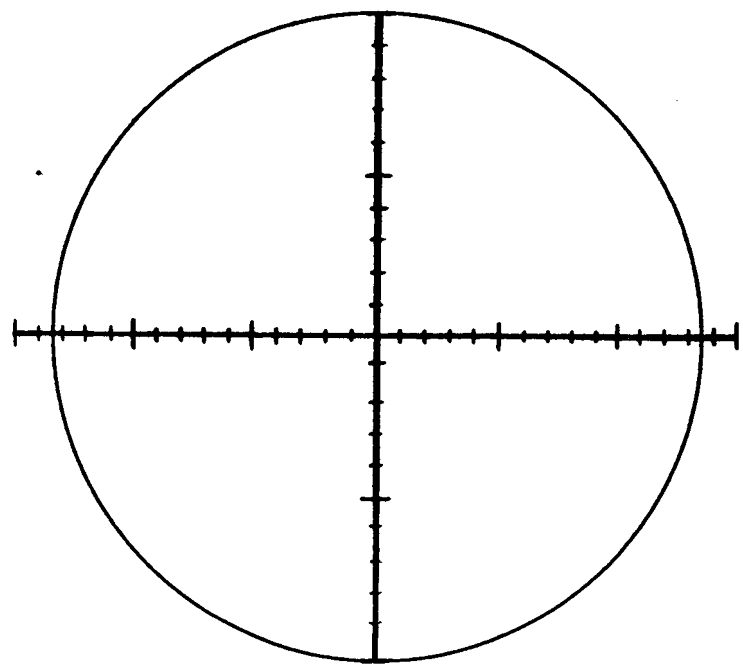
C-135 FIX ERRORS - 5.5 HOUR FLIGHT - 12/1/70
"WORST CASE" CONDITIONS





FIX ACCURACY - COAST GUARD CUTTER RUSH AT SAN FRANCISCO - 5/13/70, 7/10/70, 7/21/70

INERTIAL NAVIGATION SYSTEM - BOEING SPECIFICATION 95 PERCENT OF FIXES INSIDE THIS CIRCLE AFTER FIVE HOUR FLIGHT TIME. (NO MORE THAN 2 nmi. ERROR PER FLIGHT HOUR ON 95 PERCENT OF FLIGHTS UP TO TEN HOURS DURATION)*



*Edwin L. Hughes, "Inertial Navigation for 747 Superjet", Electronics World, 9/70, p. 27.

value of the reference transponders, because it determines the number and deployment of the transponders needed to achieve a specified accuracy for the system.

Much of the effort in the experimental program was directed to measuring the time and geographical correlations of ionosphere delay and evaluating the two methods of correcting the range measures. Figure 8 shows the correlations for Schenectady and Gander, Newfoundland on January 19, 1971. The ionospheres seem to be well correlated at the two locations which are a thousand miles apart. The correlation between Shannon, Ireland and Reykjavik, Iceland was also found to be close enough to provide range corrections within approximately 1500 feet at locations a thousand miles apart on days without unusual ionospheric disturbances.

A few times a year during the peak of the 11 year sunspot cycle solar flares cause ionospheric disturbances that can increase the propagation delay by as much as 50 percent over the average of undisturbed days. These solar disturbances are rare during sunspot minima. There was no opportunity to observe the propagation characteristics resulting from a solar flare.

A solar flare did occur on October 28, 1970 but no ionospheric disturbance resulted from it. During four days after the flare the diurnal variation in the ionosphere was observed for Shannon, Ireland; Gander, Newfoundland; Schenectady, New York; and Seattle, Washington. The day-to-day correlation for Schenectady is plotted in Figure 9. The four days were found to be correlated within approximately 1 microsecond or 491 feet in two-way ranging. A position fix is degraded by more than the ranging error because of the way the slant range measurement error projects onto the surface of the earth.

The ionosphere sometimes causes a scintillation of the amplitude of the signal received from the satellite. Scintillation is caused by horizontal variations in electron content. As the irregularities in the ionosphere move, the signal level received by an antenna from the satellite changes in signal strength. The signal level can increase above the average value by several dB and may fade below the average level by many dB. The signal fades are usually short. The deep fades are typically less than a second in duration and the fading periods are usually a few seconds to a few tens of seconds.

Scintillation fading is reported to occur frequently in tropical regions and high latitudes. It occurs less frequently at middle latitudes. A few instances of severe scintillation fading were observed at Schenectady during the experiments. The onset of the fading was usually quite sudden and the duration of the fading period would be several minutes to several hours.

The most severe case was observed on October 15, 1970, during a voice communication test with a Pan American 747 aircraft enroute from New York to Paris. Ground terminals participating in the experiment were at Annapolis, Maryland; Miami, Florida; Los Angeles, California; Seattle, Washington; Schenectady, New York. Fades as large as 30 dB were observed on the signals received with the 30 foot diameter antenna at Schenectady. Although the other participating stations reported changing signal levels, the geographical extent of the fading observed at Schenectady is not known. Excellent voice communication tests were maintained throughout the period and there was no noticeable degradation in the quality of the voice communications. It is important to note that speech is highly redundant and that short drop-outs do not have a significant effect on intelligibility. The effect on other forms of communications such as digital

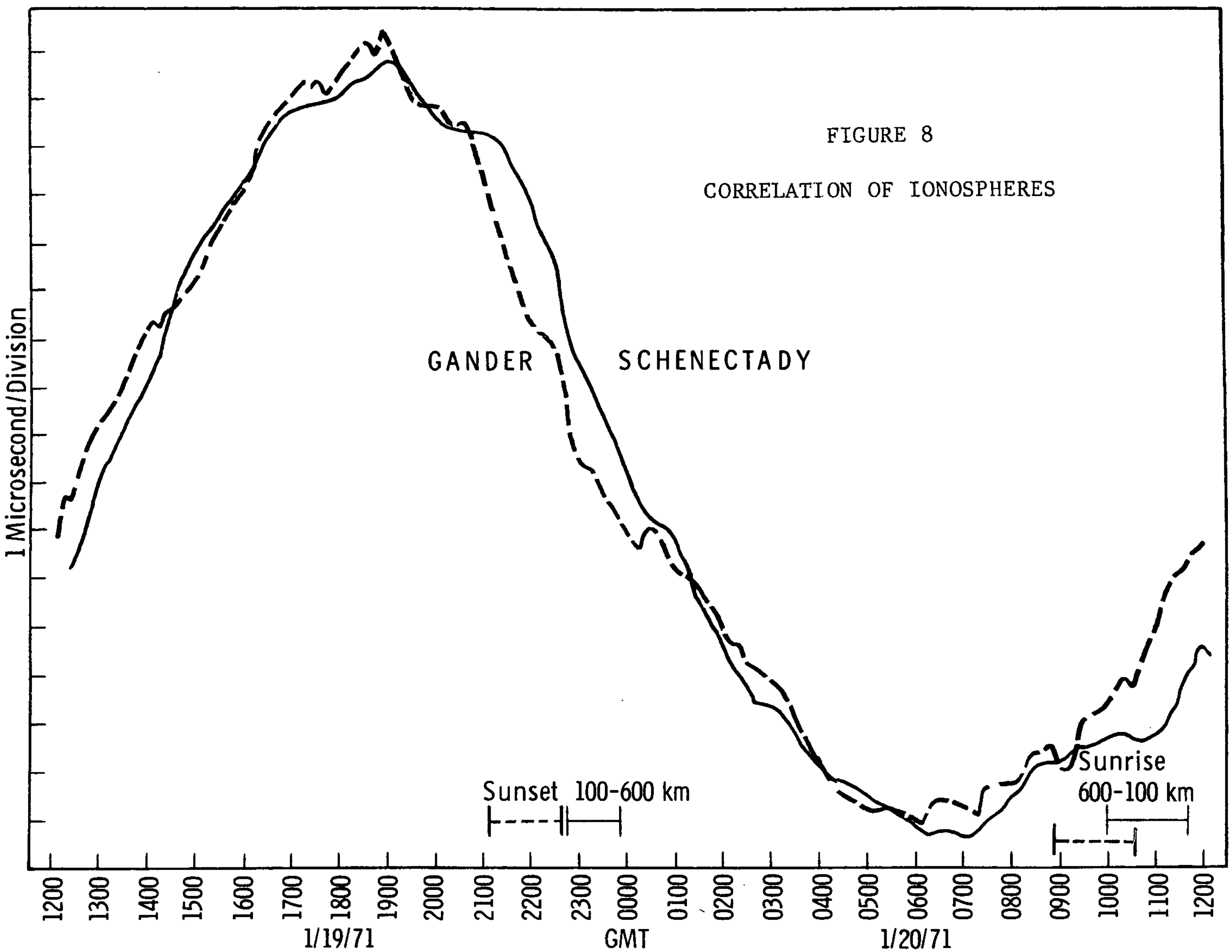
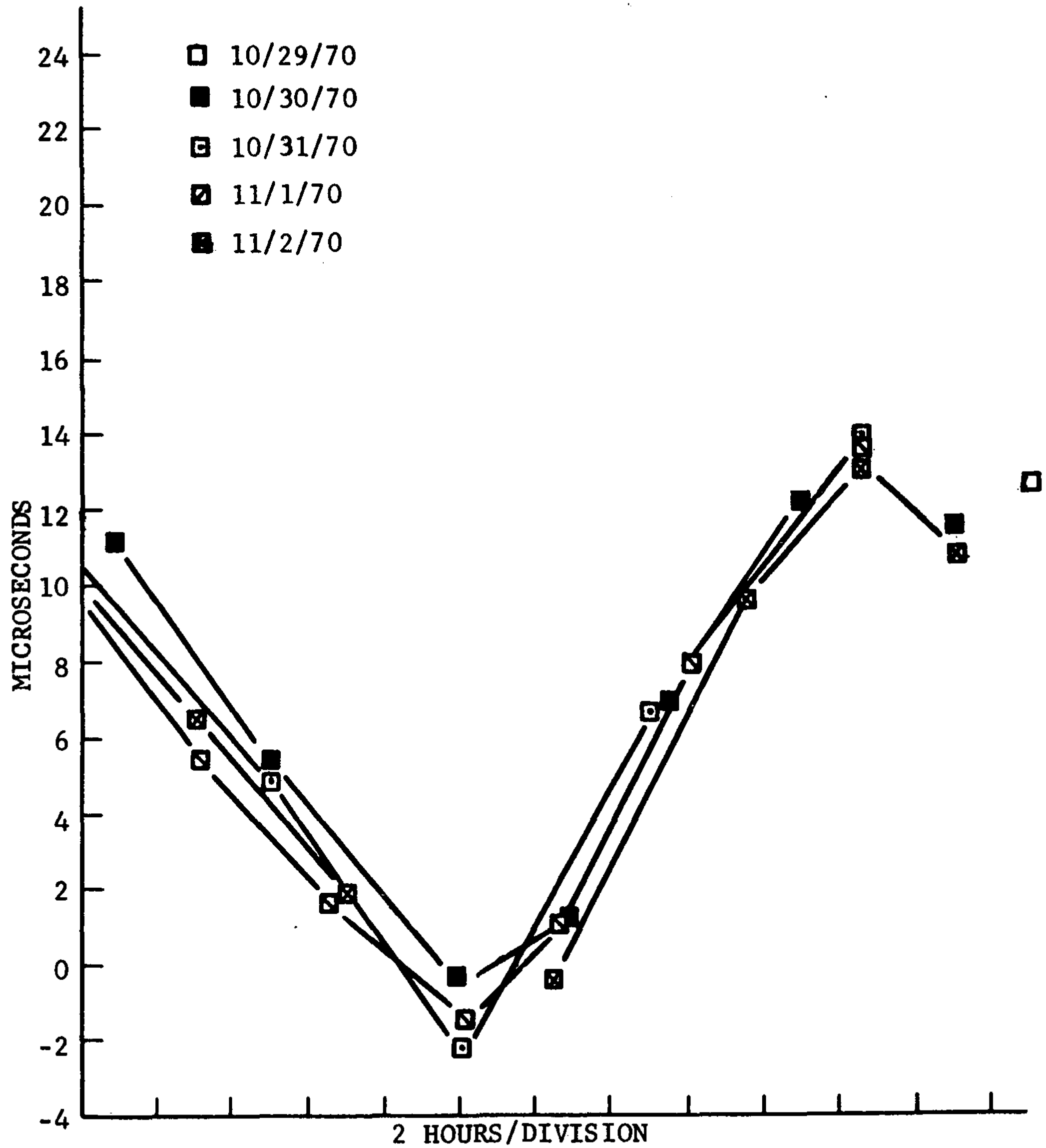


FIGURE 8

CORRELATION OF IONOSPHERES

FIGURE 9

DAY-TO-DAY CORRELATION - SCHENECTADY



which is less redundant would have to be considered in evaluating VHF communication performance when scintillation is present.

Buoy Tests

The first tone-code ranging transponder was installed in the Sea Robin buoy. Sea Robin is a spar buoy, approximately 4 feet in diameter and 15 feet long with stabilizing means designed for mooring in the deep ocean or for free floating in all sea states. During the period March through May 1969 the buoy was tested ashore, in a harbor and at a deep sea mooring near Bermuda at 32°10'N, 64°55'30"W in a joint Navy-General Electric experiment. (Navy support was through the Office of Naval Research under contract N00014-68-C0467.) The buoy was moored where the ocean depth was approximately 4000 feet using a 7000 foot line.

The tone-code transponder aboard the Sea Robin consisted of a 35 Watt solid state FM mobile radio transmitter-receiver with a 120 Watt solid state amplifier and two selectable linearly polarized dipole antennas.

Data transmission from the buoy through the satellite was accomplished by the use of the transmitter-receiver-responder unit used for the VHF ranging. A data transmission followed each range interrogation. Two data rates were tested -- 2441 bits per second and 305 bits per second.

The tone-code ranging technique was found to have two important advantages for the location and read-out of remote sensor platforms: transmission of the buoy response required a small amount of energy and was of short time duration. The radio frequency energy transmitted from the buoy was approximately 50 Watt-seconds for the ranging signal, 120 Watts for 0.3 second, and 150 Watt-seconds, 120 Watts for 1.25 seconds for the data transmission. The energy required for the transmission from a remote platform should be kept as small as possible to increase the duration of its unattended period of operation and thus reduce the cost of replenishing its energy supply.

The short duration of the interrogation and read-out sequence was important because the rolling of the buoy causes a fading of the signal at the satellite. There is an interference between the signal that is propagated directly toward the satellite and the signal that is reflected from the surface of the sea. The vertical pattern of transmissions from a buoy has a pattern of lobes and nulls. The number of the lobes is a function of the height of the antenna in wavelengths above the sea surface. The direction of the nulls depends upon the roll angle of the buoy and the tilt of the sea surface near the buoy. As the buoy rolls, the signals transmitted between the buoy and the satellite go through a fading pattern at the roll rate. Under some conditions the signal can be completely cancelled out for a short period during each roll cycle. Tone-code ranging had the advantage that duration of the interrogation, ranging and data read-out sequence was short compared to the buoy roll cycle so that a complete interrogation and response sequence could be completed between fades. Other techniques that require a lock-up around the complete transmission path from the ground station through the satellite to the buoy and return, or that utilize such low transmission power that the duration of the transmission must be long compared to a roll cycle, present difficulties that must be overcome by expensive and complicated methods such as the use of a narrow beamwidth antenna on a stabilized platform or the use or burst error correction codes in the digital transmissions.

Sea Robin was at its deep sea mooring between April 14 and 25, 1969. It was interrogated from Schenectady each three seconds during three minute interrogation periods spaced throughout each day. While at its mooring the buoy was interrogated a total of 2525 times. It responded to 1711 of the interrogations and a total of 759 latitude determinations were made. Some failures to respond were caused by buoy roll; others were due to causes purposely included in the experiment such as antenna polarization switching to observe Faraday rotation of the linearly polarized signals.

The averages of the median values for each day are plotted as the triangles in Figure 10. The wind direction and velocity as furnished by the Navy for the area are shown by the vectors near the top of the figure. It is expected that the buoy, which has a small cross section to the wind and much drag at the mooring line, responded slowly to changes in wind. The dashed line suggests the actual position of the buoy as determined from the satellite measurements. They appear to correlate with the wind directions. If it is assumed that the dashed curve of Figure 10 represents the true latitude of the buoy, the latitude determinations replotted with respect to the buoy position provide an estimate of the accuracy that was actually achieved as shown in Figure 11.

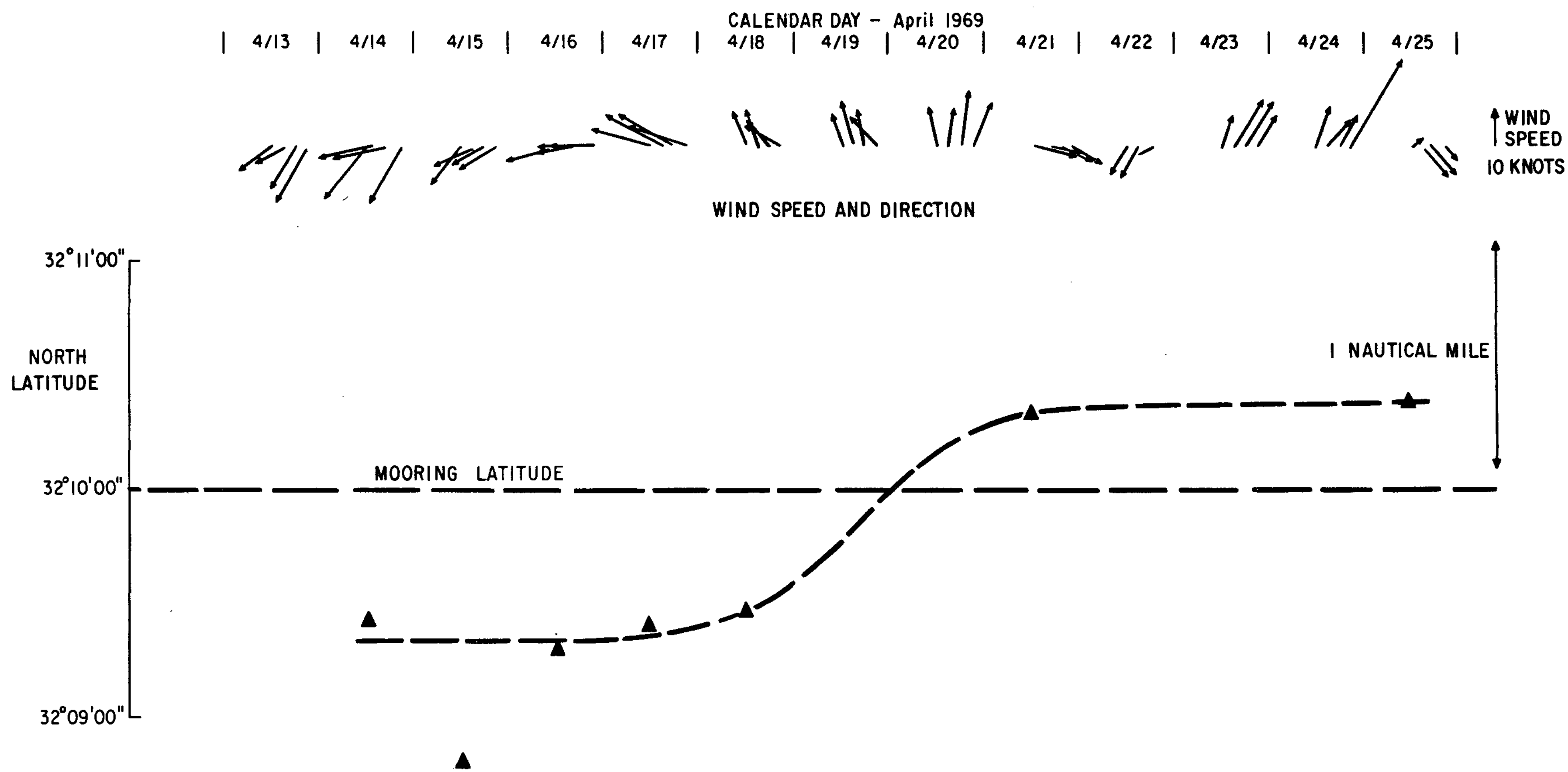
Conclusions

The experiments have shown that geostationary satellites can provide high quality, reliable, undelayed communications between distant points on the earth and that they can also be used for surveillance. A combination of undelayed communications and independent surveillance from shore provides the elements necessary for the implementation of effective traffic control for ships and aircraft over oceanic regions. Eventually the same techniques may be applied to continental air traffic control.

The tests have demonstrated that remote, unmanned platforms can be interrogated, located and their data read-out efficiently by satellites. The energy required for the location and data read-out functions is so low that the energy supplied aboard the remote platforms does not have to be replenished at frequent intervals. These tests have provided sufficient information so that it is now possible to proceed confidently with the design of operational systems for air traffic control, marine traffic control, management control of automated shipping and the synoptic location and read-out of a widespread network of remote meteorological and oceanographic sensor platforms.

FIGURE 10

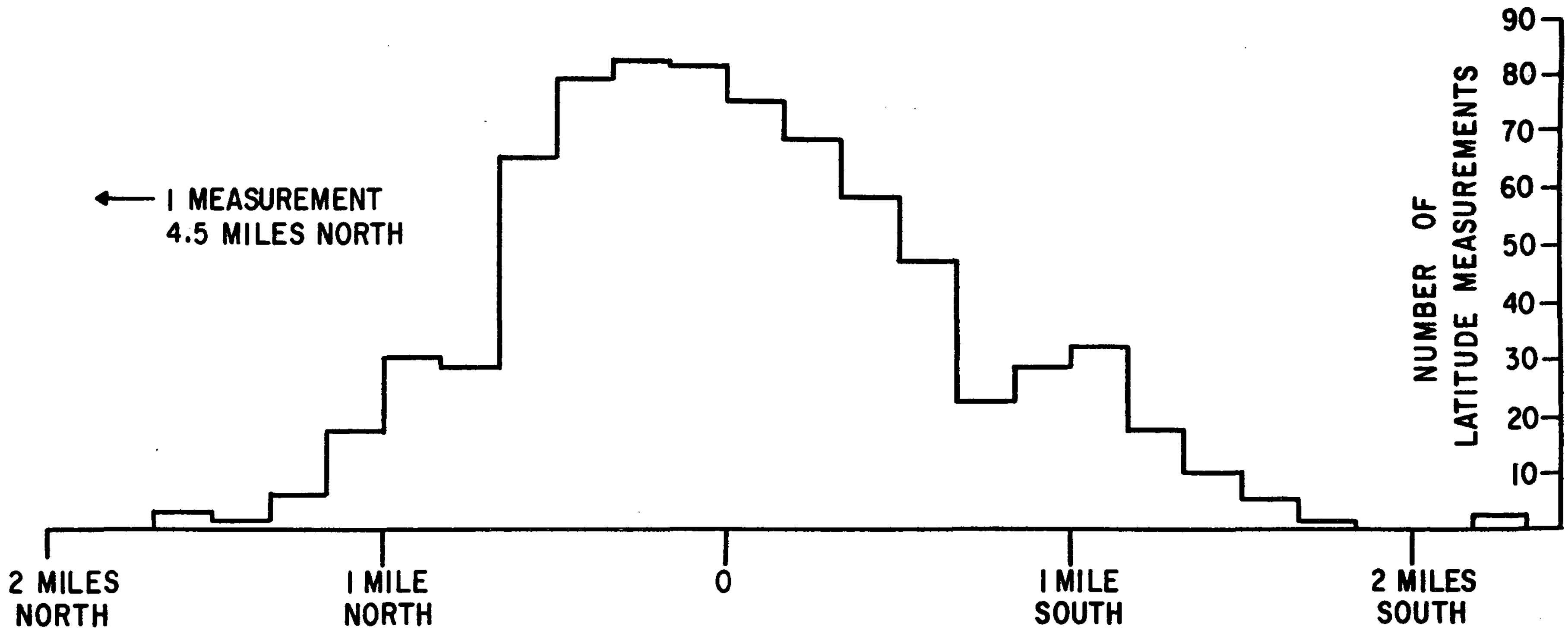
ESTIMATED BUOY POSITION



TRIANGLES ARE AVERAGE OF MEDIAN POSITIONS FOR DAYS INDICATED

FIGURE 11

DISTANCE FROM ESTIMATED BUOY POSITION (ESTIMATE OF ACCURACY ACHIEVED)



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